



A coupled human and landscape conceptual model of risk and resilience in Swiss Alpine communities

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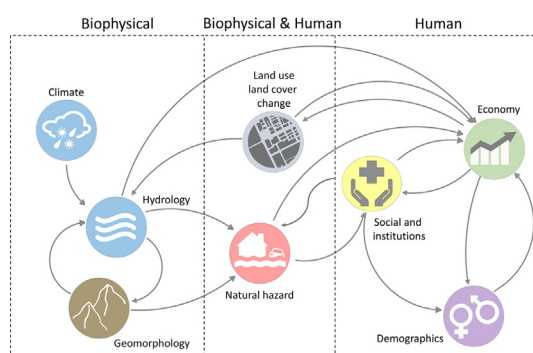
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HIGHLIGHTS

- First conceptual model of a mountain community with human and natural components
- Feedbacks highlight important interactions that increase risk and reduce resilience
- Model operationalization will predict risk and resilience of mountain communities.

GRAPHICAL ABSTRACT



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ABSTRACT

Disasters induced by natural hazards or extreme events consist of interacting human and natural components. While progress has been made to mitigate and adapt to natural hazards, much of the existing research lacks interdisciplinary approaches that equally consider both natural and social processes. More importantly, this lack of integration between approaches remains a major challenge in developing disaster risk management plans for communities. In this study, we made a first attempt to develop a conceptual model of a coupled human-landscape system in Swiss Alpine communities. The conceptual model contains a system dynamics (e.g. interaction, feedbacks) component to reproduce community level, socio-economic developments and shocks that include economic crises leading to unemployment, depopulation and diminished community revenue. Additionally, the conceptual model contains climate, hydrology, and geomorphic components that are sources of natural hazards such as floods and debris flows. Feedbacks between the socio-economic and biophysical systems permit adaptation to flood and debris flow risks by implementing spatially explicit mitigation options including flood defenses and land cover changes. Here we justify the components, scales, and feedbacks present in the conceptual model and provide guidance on how to operationalize the conceptual model to assess risk and community resilience as well as determine which shocks overcome the buffering capacity of Swiss Alpine communities.

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1. Introduction

Recent extreme natural hazards have captured the attention of the global community, consisting of policymakers, non-profit organizations, and stakeholders, to society's vulnerability to these events. Between 1980 and 2014 the number of natural hazards due to climatological, hydrological, and geophysical processes have increased by approximately 150%, and caused annual economic losses near US\$150 billion (Cutter et al., 2015). Moreover, in the period between 2005 and 2014, globally over 70% of people killed by different natural hazards were documented in mountainous countries (Klein et al., 2019). Simultaneously, these natural hazards occur within an interconnected broader social and biophysical context that may include economic crises and climate change that can further exacerbate losses and fatalities. These social and biophysical conditions are also apparent in European mountain communities that differ regarding their ability to cope with these risks and build resilience. Considering physical characteristics (e.g. topography and climate), mountain communities are particularly at risk of natural hazards. For example, in Switzerland alone economic losses in the last 45 years caused by natural hazards exceeded US\$ 13.5 billion and were geographically concentrated in Alpine regions and communities (WSL, 2017). In addition to mounting risk of natural hazards, the resilience of European Alpine communities must contend with foreseeable economic changes in hydropower generation and tourism, and social changes that may cause the loss of cultural landscapes (IPCC, 2014).

A major challenge in natural hazard risk reduction in Alpine communities is estimating how risk and resilience will change in the future (Beniston, 2003). Here, we assume risk is the probability an adverse outcome arises from the combination of a natural hazard and elements within a community that are vulnerable (Birkmann et al., 2013). These elements may include buildings, infrastructure, livelihoods or humans themselves. Resilience refers to a communities' ability to absorb and recover from a natural hazard by rebuilding fundamental services and structures in a comparatively short amount of time (Alexander, 2013). While studies have assessed current Alpine community exposure and vulnerability to natural hazards (Fuchs et al., 2015a, 2015b; Keiler and Fuchs, 2016; Röthlisberger et al., 2017), the majority of approaches to analyse future risk have not adequately considered changes in both biophysical (e.g. climate change) and socioeconomic (e.g. demography, economic crises) conditions, and their interactions (e.g. land use and land cover change). Future risk assessments have either assumed long-term changes in biophysical conditions with limited changes in socioeconomic conditions (Alfieri et al., 2015; Rojas et al., 2013) or no change in biophysical conditions but long-term projections of socioeconomic change (Cammerer et al., 2013; Cammerer and Thielen, 2013). Only one study to date considers changes in both variables (Thielen et al., 2016). The assessments mentioned above highlight a common mismatch in temporal and spatial scales when estimating future risk of natural hazards. Using flood risk as an example, assessments considering a time horizon of 100 years may use climate models to produce future weather events that flood a community and the locations of present day buildings and infrastructure to determine assets at risk. Utilizing this approach can both over- or under-estimate flood risk because the disparity in spatial and temporal scales dismisses community level socioeconomic changes in time that could reduce flood exposure through adaptation (e.g. land abandonment) or increase flood exposure through settlement densification. Methods to assess community resilience to natural hazards are various (see Cutter (2016) for review), but unlike risk, community resilience is rarely, if ever, estimated for the future (Frazier et al., 2013). For example, approaches like resilience composite indicators (Foster, 2012; ISDR, 2005; Peacock et al., 2010) combine variables that represent social, economic, institutional, and infrastructural components of a community to quantitatively measure resilience to natural hazards. Although resilience indicators could be applied for periods in the future, they are often employed to determine present day, baseline measures of community resilience. Further,

analysis of future resilience is not possible with indicators because data is not available or highly uncertain for variables (e.g. unemployment, poverty, home values) in the future. Thus, there is a need for a risk and resilience assessment method for Alpine communities that considers future spatial and temporal changes and the interactions between biophysical and socioeconomic conditions.

Researchers in computer modelling within hydrology and geomorphology have begun to address the interactions between society and nature within the context of natural hazards. Studies in socio-hydrology (Di Baldassarre et al., 2013) are coupling differential equations to represent linkages within a community (e.g. society's awareness of flood risk motivating political decisions to change land use) that contribute to flood risk and resilience (Ciullo et al., 2017), but these methods remain less suitable for Alpine communities (Fuchs et al., 2017a). First, floods in Alpine communities are largely affected by geomorphic processes (e.g. sediment deposition) that alter a river's capacity to convey water, and these processes are not considered in socio-hydrology (Rickenmann and Koschni, 2010). Secondly, a major drawback in socio-hydrology approaches is the lack of a spatial component, which is quite relevant in risk (e.g. location of building with relation to a flood) and resilience (e.g. constructing protective infrastructure) assessments. In geomorphology, researchers have developed coupled human landscape systems (CHLS) (Werner and McNamara, 2007) that emphasize linkages, feedbacks and processes for biophysical and socioeconomic components represented at multiple scales (spatial and temporal). A key factor in a CHLS is that humans have a discernable impact on the landscape (e.g. increasing erosion through deforestation), while in turn, the landscape has an impact on human decisions (e.g. settlement abandonment after a debris flow hazard). However, existing CHLS are few, with examples focusing on coastal regions affected by storm surge floods, tourism, and beach nourishment (McNamara and Werner, 2008; Murray et al., 2013), and a separate example for New Orleans impacted by storm surge, river and sea level rise flooding and economic agents (e.g. employers, tourists, laborers) (Werner and McNamara, 2007). To date, no attempt has been made to develop a CHLS for mountain communities that are exposed to natural hazards.

Despite the growing emphasis (e.g. Biggs et al., 2012; Hossain et al., 2018; Verburg et al., 2016) on dynamic relationships between human and natural systems, previous studies (e.g. Joakim et al., 2016) focused on the dynamics within human components (e.g. food security, mobility, population, risk management, and policy (e.g. Fuchs et al., 2017b))) without considering the dynamic relationship within natural systems and between human and natural systems. Likewise, there remains a total disconnect between the biophysical and socioeconomic components in most assessments of future risk and resilience trajectories for Alpine communities. Yet, biophysical and socioeconomic processes that underpin the dynamics of mountain communities are linked, constitute feedbacks and occur at various spatial and temporal scales (Fuchs et al., 2013). Fig. 1 provides an overview of how the dynamics (e.g. interactions, feedbacks) between human and natural systems influence the risk and resilience of mountain communities. For example, changes (e.g. deforestation) in land systems influence hydrological processes (e.g. surface runoff, flow velocity), leading to an increase in the risk of natural hazards (e.g. floods damaging buildings and infrastructure), which negatively influences an economy (e.g. may cause less employment and income from tourism, more dependency on social benefits), which in turn creates a political pressure to restore the land use system, that reduces the risk and increases the resilience to floods in the community (Fig. 1). Therefore, consideration of dynamic relationships (e.g. interactions, feedback) between human and natural systems of mountain communities is essential for managing the long-term risk and resilience of mountain communities.

Given the need to assess future risk and community resilience in Alpine communities, and the lack of suitable methods described above, we make a first attempt to develop a conceptual model of a CHLS considering the dynamic relationships (e.g. interaction, feedback) between

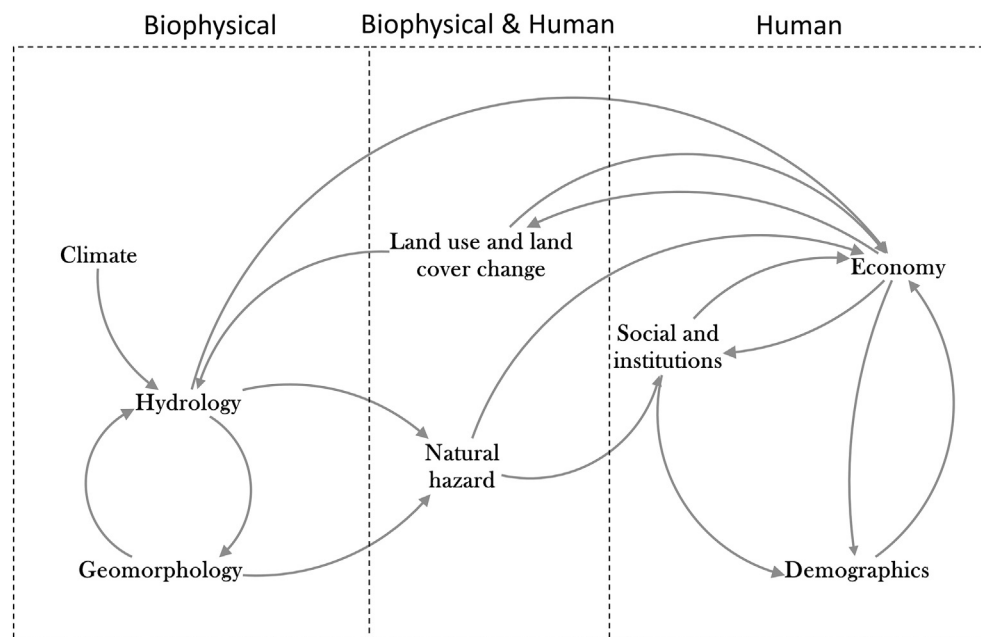


Fig. 1. Causal loop diagram for Alpine communities with linkages between biophysical and human model components.

human and natural systems for Swiss Alpine communities. We strive to achieve this overall aim by developing a conceptual model that captures three mountain communities in Switzerland and answering the following research questions: (1) What are the key indicators and processes required to describe the human and natural systems in the Swiss Alpine communities? (2) What are the interlinkages and causality of those indicators and processes? (3) What feedbacks exist within and between both human and natural systems? (4) What are the policy implications of the dynamic relationships (e.g. interaction, feedbacks) between human and natural systems? To answer these questions, we reviewed literature and engaged an interdisciplinary team to develop a conceptual model, which was further discussed with the stakeholders in three Swiss mountain communities to crosscheck the conceptualization of the complex dynamics (indicators, interactions, feedbacks) between human and natural systems. In summary, Section 2 introduces the conceptual framework, methodological approach and study sites. Section 3 presents the indicators of biophysical and human systems, before discussing the feedbacks within and between the two systems. Section 4 introduces the summary of the results and policy implications, before arguing specific challenges in operationalizing complex dynamics (indicators, interactions, feedbacks) between human and natural systems. It is intended that the findings from the present study will be useful in understanding the complex dynamics between human and natural systems in order to explore the risk and resilience of Swiss Alpine communities in response to changes in human and natural systems (Section 3).

2. Study area and methods

2.1. Study area

To illustrate our conceptual model, we selected a mountainous part of the Aare river catchment (called Oberhasli) in Switzerland whose topography is characterized by steep slopes, isolated valleys and a river system that is partly controlled by dams for hydropower (Burger, 2017) (Fig. S1 a). The catchment area is approximately 450 km², with elevations between 570 and 3700 m, and land cover typical for Swiss Alpine communities (Fig. S1 b). Meiringen, Innertkirchen, and Guttannen are settlements in the Oberhasli catchment (Fig. S1 b) and typify Swiss mountain communities facing human and environmental risks. Natural

hazards cause a large amount of damage and economic loss in the Oberhasli communities (Figs. 2 and 3). Between the years 1972–2015 total economic losses due to floods, debris flows, landslides, and rockfall was US\$ ~90 million. During this period, floods accounted for 85% of the losses, 13% of the damage was caused by debris flows and a small percentage of damage (3%) was caused by landslides and rockfalls. Mean annual damages for all natural hazards was US\$ ~ 900,000, but a disproportionate amount of the damage occurred during a few events. For example, in August 2005 continuous precipitation for three days caused many floods and debris flows in Switzerland (Rickenmann and Koschni, 2010). In Oberhasli, this event alone accounted for 80% of the damages due to natural hazards in the last 33 years. This highlights how high magnitude weather events and the resulting natural hazards can place an extraordinary amount of economic strain on communities in a short period.

The Oberhasli catchment faces various socio-economic risks, ranging from a high dependence of its economy on single resources (e.g. snow for winter tourism or water for hydropower generation), the small tax basis (recipient of national fiscal equalization and subsidies to farmers) and a shrinking demographic base (a lack of young families and an increase in pensioners) (Müller-Jentsch, 2017). These socio-economic challenges can be internal to the catchment but are also external such as the rise in the value of Swiss francs or the depreciation of the Euro adversely affecting the capacity of European tourists to visit the Swiss Alps, or even the second home referendum in Switzerland, thus influencing the local economy (Segessemann and Crevoisier, 2015). It is important to note that the biophysical and socioeconomic shocks interact to determine social-ecological and biophysical outcomes for the Oberhasli catchment.

2.2. System dynamics approach

We opted to use a system dynamics approach to develop a conceptual system model of factors influencing risk and resilience in Swiss Alpine communities, in the form of a causal loop diagram because it enables identifying key variables, interactions and feedbacks. System dynamic approach is a way of thinking that emphasizes understanding the behavior of complex systems over time (Ford, 1999; Forrester, 1997). This approach provides opportunities to: 1) consider the whole system instead of focusing on parts of a system (Meadows, 2008) and;

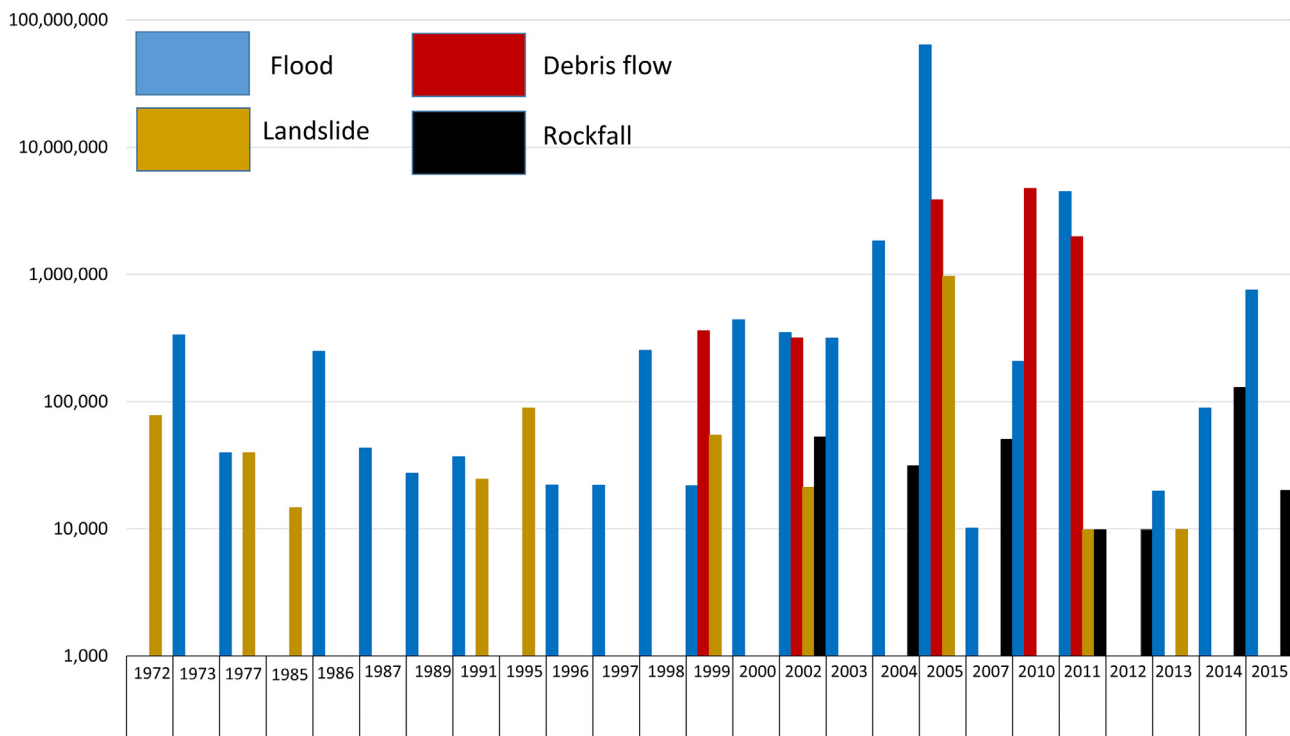


Fig. 2. (a) Time series of annual damage costs due to natural hazards occurring in the Oberhasli catchment. Damage cost are corrected for inflation, rock fall data are included in the database from 2002 onwards, and prior to 1999 the lack of debris flow damages is due to no distinction between floods and debris flows. Note that increasing damages over time may be due to increased data availability (Hilker et al., 2009; Swiss Federal Institute for Forest Snow and Landscape Research (WSL), 2015).

2) synthesizing the complex interactions (e.g. delays, feedbacks, and non-linearity) between human and natural systems (Hossain et al., 2017a; Hossain and Szabo, 2017). A system dynamic approach starts with the development of a conceptual system model, called a causal loop diagram (Sterman, 2000). A causal loop diagram simplifies the complexity of a real-world system and helps understand the cause and effect relationships between variables and identifies closed loops (e.g. where outputs of a system are routed back as inputs) that create either positive or negative feedback loops (Hossain et al., 2017b; Inam et al., 2015). A positive feedback loop depicts the cause and effect between variables and can subsequently lead to growth (increasing or decreasing) in a system. Positive feedback loops are also known as reinforcing loops and tend to cause dynamic behavior and system instability. In contrast, negative feedback loops are often known as balancing loops, and act to reduce or counteract the results of a change or growth in the system (Ford, 2010). For example, a positive feedback occurs when deforestation increases regional temperature, which increases the occurrence of forest fire, and in turn causes further deforestation. Introducing reforestation in this positive loop acts to reduce deforestation and could transform the positive feedback into a negative feedback loop.

The development of a conceptual system model through a causal loop diagram serves as a basis for understanding a system and complex dynamic relationships (e.g. delays, feedbacks, and non-linearity) between its components, which shape the behavior of the system (Hossain et al., 2017b; Joakim et al., 2016; Leenhardt et al., 2017). In addition to providing a basis for sustainability assessments or the co-evolution of human and biophysical systems, causal loop diagrams are a component of system dynamic modelling that quantifies changes in a system through simulation (Kotir et al., 2016; Sterman, 2000). The development of conceptual models using a system dynamic approach has widely been used in assessing the sustainability of industrial ecosystems (Mota-López et al., 2018), water resources (Guo et al., 2001; Inam et al., 2015; Kotir et al., 2016), coastal hazards (Joakim et al., 2016), coral reefs (Leenhardt et al., 2017) and the social-ecological dynamics of

agricultural systems (Hossain et al., 2019; Hossain et al., 2017b; Kopainsky et al., 2015; Robert et al., 2017).

2.3. Conceptualizing the coupled human and landscape (CHL) model of Swiss Alpine communities

In summary, the system dynamics approach consists of eight steps (SI Fig. 1), among which, the first four steps are qualitative and the remaining steps (5th to 8th) are quantitative (Ford 2010). The qualitative approach consists of the four following steps: 1) problem familiarization to get acquainted with the problem; 2) identification of key variables of the systems and 3 & 4) development of a conceptual model by defining the relationships (interactions, feedbacks) and identifying positive and negative feedbacks loops. In this paper, a qualitative research method (SI Fig. 1) has been used to develop a coupled human and landscape (CHL) model for Swiss Alpine communities. The use of a qualitative approach to develop a conceptual model is based on a literature review, and has been widely applied in social marketing (Domengan et al., 2016), community resilience to tourism (Bec et al., 2015), assessing sustainability of industrial ecosystems (Mota-López et al., 2018), soil carbon management (Amin et al., 2020) and integrating social-cultural concepts into social and natural systems (Muhar et al., 2017).

In general, the method of this study comprises three research steps: 1) identifying variables and conceptualizing relationships (interactions and feedbacks) among the variables by using literature review to develop a CHL model; 2) consulting with local expert stakeholders in order to verify relationships conceptualized in the CHL model; and 3) discussing with local (e.g. interdisciplinary research team), national (e.g. Swiss Geoscience) and international (e.g. EGU) expertise before finalizing the CHL model.

We develop a CHL model (Fig. 1) by reviewing literature and using a system dynamics approach for Swiss Alpine communities. Fig. 1 provides an overview of how the dynamics (e.g. interactions, feedbacks) between human and natural systems influence the risk and resilience

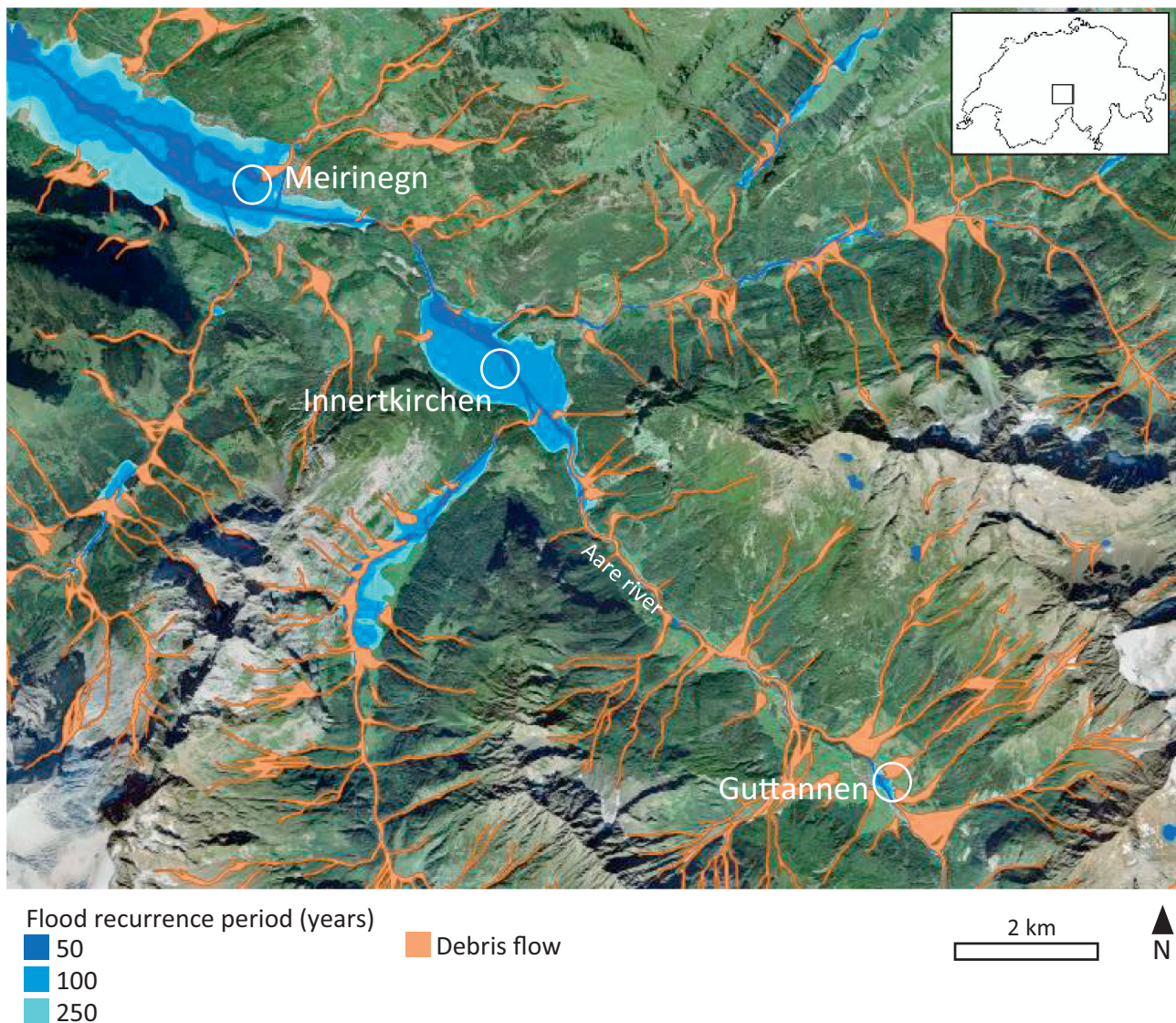


Fig. 3. Spatial extent of potential flooding and debris flow in the Oberhasli mountain communities (Federal Office for the Environment, 2008).

of Swiss Alpine communities. The biophysical components of CHL model comprises climate, hydrology, and geomorphology, which influence natural hazards, which in turn are linked to the social components of the CHL model such as demographics, economy, social practices and institutions. The economic component is linked to land use and land cover changes, which influences both the economy and hydrology components of the CHL model. All these dynamic relationships (e.g. interactions, feedbacks) between human and natural systems influence the risk and resilience of Swiss Alpine communities. For example, climate change (more high precipitation events) and changes (e.g. deforestation, housing infrastructure) in land systems influence hydrological processes (e.g. surface runoff, flow velocity), leading to an increase in the risk of natural hazards (e.g. floods), which negatively influences the economy (e.g. income, dependency on social benefits), which in turn creates a political pressure to restore the land use system, reduce the risk and increase the resilience to floods in the community (Fig. 1).

We used the overall CHL model (Fig. 1), review of literature, secondary data and expert knowledge to conceptualize the full conceptual CHL model (Fig. 4) for Swiss Alpine communities. The literature review focused on the studies on risk and resilience, drawing on scientific articles, projects and thesis reports. Though we focused on the literature written in English, we also reviewed literature written in German in order to capture the local context of the study area. We may have missed some

studies in our review but we expect that our approach offer adequate material to develop a full CHL model. Considering the system dynamics approach, the conceptualization of the CHL model comprises four steps: 1) identification of key variables (factors), which influence the risk, and resilience of Swiss Alpine communities; 2) defining the relationships among those variables; 3) conceptualizing feedbacks among the variables and; 4) identifying positive and negative feedbacks. Table 1S provides the overview of the variables, processes, scales and literature used in developing the causal loop diagram for a coupled human landscape system for Swiss Alpine communities.

Besides using the review of literature (including video reports (e.g. SRF, 2017, 2003, 1999) of past hazard events in the Oberhasli valley and other Swiss alpine areas), we also discussed with local stakeholders in order to ensure the selection of relevant variables, and realistic conceptualization of dynamics relationships (interactions, feedbacks) within and between human and natural systems. In particular, we visited three communities (Innertkirchen, Meiringen and Guttannen) to conduct three expert consultations with representatives of the local government, the managers and planners working in the municipalities of Oberhasli catchment. The average time for each consultation was an hour. A research assistant with an academic background (geography, risk and resilience) was involved in this consultation as a language translator to ensure the correct interpretation of the consultations. All

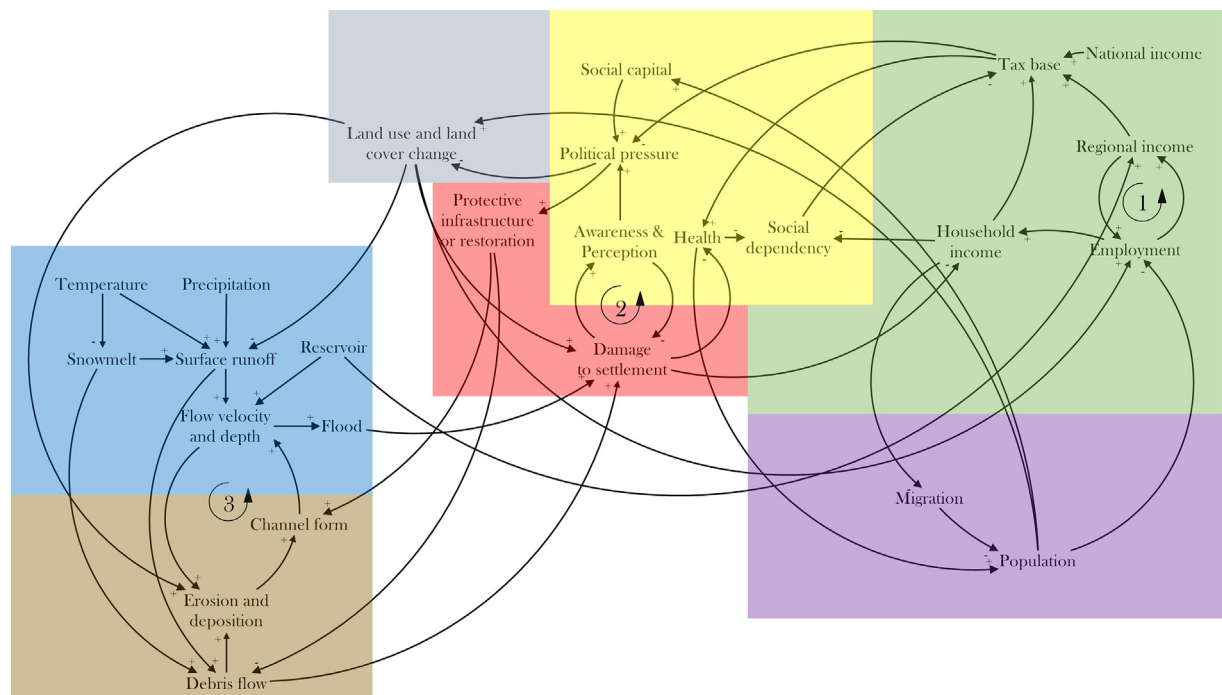


Fig. 4. Causal loop diagram for a coupled human landscape system for Alpine communities. Shading demarcates components that include geomorphology and hazard (brown), climate and hydrology (blue), land use land cover change (gray), hazards (red), social/institutions (yellow), economy (green), and demographics (purple).

participants were informed that their identity would be kept anonymous. Three expert consultations were conducted in December 2018. During the expert consultations, experts were briefly introduced with our overall and full conceptual model. After the brief introduction, experts were asked about the variable selection and relationships among the variables to ascertain if all these conceptualizations are depicting the real context of the three communities (Innertkirchen, Meiringen and Guttannen). The main topics of the expert consultation (using an unstructured list of questions) during the field visit was not limited to the variables and relationships, but extended to overall risks and how communities are dealing with those risks overtime in that catchment. In addition, we also discussed with further regional experts and drew on interviews conducted on other stakeholders such as by Burger (2017).

Feedbacks received from participants in a national (e.g. Swiss Geoscience meeting 2019) and international (e.g. European Geosciences Union 2018, International Conference on Geomorphology 2017) events were useful in finalizing the assumptions of relationships and conceptualization of the CHL model. The main idea of expert consultations was to ensure the selection of relevant variables, and realistic conceptualization of dynamics relationships (interactions, feedbacks) within and between human and natural systems. For example, our initial model includes a linkage between climate and land use and land cover change. Considering the feedbacks received during discussion with experts, we

excluded the relationships, as the climate may not be significantly influenced by local land use change. In addition, the linkages among natural hazards, economy (e.g. tax base), social practices and institutions (e.g. political pressure) were conceptualized and revisited before including in the final CHL model.

3. Results

Fig. 4 is a causal loop diagram of a Mountain Community Coupled Human Landscape System (MC-CHLS), which includes variables, processes and relationships for both biophysical and socioeconomic components. All definitions for variables, processes and their spatial and temporal resolutions are provided in Table 1S. In the following section, we provide the rationale for the conceptual model components and illustrate their necessity using data that is specific for Oberhasli.

3.1. Biophysical system

MC-CHLS focuses on two natural hazards or biophysical shocks because they have had the highest consequences so far: debris flows and floods. A debris flow is a gravity-driven mixture of water, mud, and boulders that behaves somewhat like a fluid and moves quickly down-slope (Takahashi, 2014). Debris flows commonly occur in high mountain locations with steep slopes, available sources of sediment and

Table 1
Feedback loops identified for a coupled human landscape system for Swiss Alpine communities.

Loop No.	Description	Balancing or reinforcing
1	Debris flow → Damage to settlement → Awareness and perception → Political pressure → Protective infrastructure or restoration → Debris flow	Balancing
2	Land use and land cover change → Employment → Regional income → Tax base → Political pressure → Land use and land cover change	Reinforcing
3	Land use and land cover change → Damage to settlement → Household income → Tax base → Political pressure → Land use and land cover change	Balancing
4	Population → Employment → Household income → Migration → Population	Reinforcing/ Balancing
5	Population → Employment → Regional income → Tax base → Health	Reinforcing

water (e.g. rainfall or snowmelt) (Badoux et al., 2009). Floods can be produced by a combination of large quantities of rainfall in a short period, saturation of the soil with water and snow melt. During fluvial flood conditions, the volume of water in a river exceeds the conveyance capacity of the channel and overbank flooding occurs. Floods are geomorphically important because the moving floodwater changes the shape of a river by exerting force on the bottom and sides of the channel (Baker et al., 1988). Moreover, flash floods are particularly dangerous for mountain communities because they develop rapidly and allow limited amounts of time for preparedness or evacuation of people within the floodplain (Jasper et al., 2002). Flash floods can also mobilize large quantities of woody debris that are transported downstream. Woody debris within the river can accumulate behind bridges and weirs and form blockages that may result in flooding or drastic channel changes (Comiti et al., 2016).

Landscape processes in MC-CHLS are driven by sub-daily, catchment scale weather variables that include temperature and precipitation (Fig. 4, shaded blue). Both weather inputs are needed to generate debris flows and floods affecting mountain communities. Of importance are extreme weather events (e.g. intense precipitation and warm days), which are expected to occur more frequently in the Alps in a warmer climate (Rajczak et al., 2013), and will produce natural hazards of unprecedented magnitude and greater frequency (Keiler et al., 2010; Köplin et al., 2014; Stoffel et al., 2014). Specific to Oberhasli, climate records from 1960 to 2017 indicate warmer and wetter trends (Fig. S2 a, b) that may contribute to future debris flow and flood events (Scherrer et al., 2016).

In MC-CHLS weather inputs are positively linked to the hydrological component of MC-CHLS, which estimates the amount of surface runoff in the Oberhasli catchment from the combination of precipitation, snow melt and land cover. Land cover is an important variable in MC-CHLS because it influences catchment response (surface runoff) to rainfall events through interception and infiltration (Robinson et al., 2003). These processes alter duration and peak river discharge (Brath et al., 2006; Reynard et al., 2001) and may change possibilities of flooding in Swiss Alpine communities. Specifically, land cover transitions in Alpine regions which are undergoing land abandonment and afforestation (Price et al., 2015) can result in higher infiltration rates, higher tree evapotranspiration, lower runoff (Alewell and Bebi, 2011) and lower flood hazard. Land cover in the Oberhasli exhibited a minor transition after 1900 when grassland became forest, but in the last 80 years land cover types have remained stable (Fig. S3 a) with grass being the dominant land cover type at lower elevations where mountain communities live (Fig. S1 b). Moreover, land cover changes have an important role in exacerbating or buffering the effects of rainfall events that are geomorphically effective in transporting sediment (Coulthard and Macklin, 2001; Piégay et al., 2004). Studies show that vegetated landscapes produce lower runoff and less sediment yields (Bathurst et al., 2017; Van Rompaey et al., 2002). For these reasons, on decadal time scales MC-CHLS considers land cover changes (Fig. 4, shaded gray) that are positively or negatively linked to surface runoff. Besides land cover's effect on hydrology, sediment yield is also lower from vegetated landscapes because roots stabilize soil (Reubens et al., 2007), while foliage and accumulating humus protects soil from raindrop impact (Piccolo, 1996). MC-CHLS includes these processes by linking land cover changes to erosion and deposition of sediment.

In MC-CHLS, on a sub-hourly time scale the resulting surface flow from the hydrological component is routed over the landscape (e.g. hillslopes, floodplain) and river channels to produce flow velocity and water depths. Hydrological processes in MC-CHLS also consider human impacts on the river. For example, sub-hourly discharge is controlled at the location of dams and this allows the retention of water in reservoirs during rainfall events that could flood downstream mountain communities. It has been observed that this process can attenuate peak flows by 10–20% in Alpine catchments (Hauenstein, 2005). In Oberhasli, since 1932, humans have significantly altered the hydrology of the

catchment through hydropower operations, and today the catchment contains nine power plants and five reservoirs. The effects of hydropower on hydrology are apparent in the discharge from the catchment (Fig. S2 c) (Bruder et al., 2016; Tonolla et al., 2017). The overall result of holding and releasing water to generate power creates a greater number of low flows, attenuates higher flows, and offers the mountain communities protection from flooding. Additional evidence for human impact on flooding is the previously mentioned August 2005 flood that had a potential peak discharge (Fig. S2 c) reduction of 20% due to the retention of water in the reservoirs (Schulte et al., 2015).

In MC-CHLS protective infrastructure (e.g. levees) can be constructed adjacent to rivers and upgraded and maintained on decadal time scales. This infrastructure affects channel form by confining flow and shields mountain communities from low return period flood events. The importance of levees is marked by their frequency of occurrence, for example in Oberhasli, 45% of the Aare river's main channel is protected with levees (Canton Bern, 2009) that are located in or near the communities of Meiringen and Innertkirchen. In contrast to levee building, in MC-CHLS existing levees can be removed to reconnect rivers to floodplains and natural ecosystems. This action protects mountain communities against floods by restoring the water storage capacity of floodplains and reducing flood levels (Opperman et al., 2009). Levee building and removal are "hard" and "soft" adaptation measures that communities can employ to reduce flood hazard and are part of the land use/land cover component of MC-CHLS (Fig. 4, shaded gray).

The output of the hydrological component in MC-CHLS are floods which are biophysical shocks positively linked to damage to settlements. These floods may damage buildings and infrastructure in Swiss Alpine communities, leading to monetary costs. Importantly MC-CHLS explicitly considers space, specifically topography which largely determines the propensity and location of flooding in the Oberhasli communities. Flood risk is lowest in Guttannen because the community is located approximately 10 m above the Aare river channel and this topographic setting would require a significant amount of discharge to produce flooding. This is illustrated in flood hazard maps for Guttannen that shows no flooding within the community for a rare, high magnitude flood event with a recurrence period of 250 years (Fig. 3). In contrast, Innertkirchen and Meiringen are more at risk of flooding because they are located downstream from tributaries that contribute more discharge to the Aare river and the communities are situated on topography that is lower in elevation. Here for these two communities, floods with a recurrence period of 100 years affect large parts of the community (Fig. 3).

In addition to hydrological processes, simultaneously the geomorphic component in MC-CHLS (Fig. 4, shaded brown) replicates changes to the landscape's surface elevation using sediment transport laws that determine the quantity and size of sediment eroded and deposited on catchment hillslopes, floodplains, and river channels. Sediment characteristics and availability are an important factor in determining flood risk because they highly determine channel form (Krapesch et al., 2011). Considering this, a feedback in MC-CHLS exists to represent floods (e.g. events with high flow velocity and depth) that change the conveyance capacity of a river channel through erosion (deepening and widening) and/or deposition (shallowing and narrowing) and partly determines the occurrence of future flooding (Fig. 4, loop 3). This feedback can increase flood magnitude, frequency, and duration when channels aggrade and increase the likelihood of out-of-bank flow (Lane et al., 2007; Raven et al., 2009). The resulting geomorphic linkages and feedbacks in MC-CHLS, when applied to the Oberhasli, broadly allow discharge, sediment supply, and transport to drive long-term changes (100 years) in community flood risk.

Debris flows within MC-CHLS are the second biophysical shock that can threaten mountain communities due to their high flow velocity, impact forces and long runout. Conditions, which contribute to the initiation of debris flows are steep hillslopes and channels, the availability of sediment and sufficient water to maintain the needed water-

sediment ratio during the transport of sediment (Costa, 1984; Jakob et al., 2005). Debris flows are often triggered by intense rainfall or prolonged precipitation events that result in high surface runoff, but may also be driven by rapid snowmelt or rain-on-snow events (Borga et al., 2014; Rickenmann and Zimmermann, 1993; Rössler et al., 2014). For this reason, MC-CHLS links debris flows to the mentioned climate variables (e.g. rainfall) via the hydrological component (Fig. 4). In Alpine catchments, debris flows affect mountain communities located on alluvial fans and/or rivers and a long tradition exists towards the prevention of debris flows. These measures include reforestation and soil bioengineering that is often complemented by civil engineering structures such as check dams, embankments and sediment retentions (see Piton et al., 2017 for French overview and Keiler and Fuchs (2018) for European overview). The different combination of civil engineering structures aim to prevent debris flows or reduce debris flow magnitude by: 1) retaining sediment in the headwaters, 2) consolidating slopes, 3) preventing incision and lateral erosion in the channel, and 4) regulating sediment flux to the fan or receiving river (Bergmeister et al., 2008; Piton et al., 2017). In MC-CHLS the linkage between protective infrastructure and debris flows accounts for debris flow reduction measures (Fig. S4). Among the communities in the Oberhasli, debris flow risk is highest in Guttannen because of its proximity to steep mountains and many debris flow fans (Fig. 3). For example, previous debris flows occurring near or downstream from Guttannen have blocked or suspended road access to the village in 2009, 2010, 2011, 2013, and 2015 (Canton Bern, 2018). The other communities in the Oberhasli have lower risk of debris flows, but the road infrastructure connecting the communities and settlements have a high risk.

Processes that cause mountain hazards can also cascade and develop into multi-hazards (Kappes et al., 2012). These natural hazards are often the outcome of processes that commence high in the mountains (e.g. thawing permafrost, glacial melting) and are triggered when thresholds are crossed, and chains of events are set in motion (e.g. debris flow producing flooding). Multi-hazards may cascade downslope and ultimately produce hazards within communities in populated valleys and have effects that can extend to low mountain areas (Kappes et al., 2012). MC-CHLS considers floods and debris flows that together can interact to produce a multi hazard. For example, a debris flow can transport a large sediment load ($>50,000 \text{ m}^3$) into a river over a short duration of time (24 h) and cause river damming or channel aggradation (Korup, 2004). Either of these processes can result in a redirection of the river (e.g. avulsion) that floods previously less exposed or unexposed communities. A multi-hazard in the Oberhasli catchment occurred upstream of Guttannen on August 2005, when a debris flow with $\sim 500,000 \text{ m}^3$ of sediment (Huggel et al., 2012) partially blocked the river Aare and produced a flood in Guttannen when the river was redirected towards the community. Another result of multi-hazards near Guttannen is channel aggradation in the Aare river due to the increased frequency of debris flow events with high sediment volumes in the last decade (Kober et al., 2012). For example, after the 2005 flood, up to 1 m of sediment was deposited on the bed of the Aare river near Innertkirchen (Rickenmann et al., 2014). These changes to the Aare river channel morphology have reduced the conveyance capacity of the channel and consequently will lead to a higher flood risk.

3.2. Human system

The economic component of MC-CHLS (Fig. 4, shaded green) comprises damage to settlements (e.g. due to debris flow and floods), tax base, employment, households, regional, and national income. In MC-CHLS damages to settlements due to biophysical shocks are negatively linked to household income, which decreases further in situations of socioeconomic crisis (Brouwer et al., 2007). Low household income (i.e. per capita income) increases pressure on the communities' tax base system. In the absence of income at household level, the communities receive national and also cantonal fiscal equalization and many

members of the community depend substantially on allowances and benefits from the government (Faetanini and Tankha, 2013). This economic part of the human system enables communities to absorb shocks and recover from losses caused by the impact of natural hazards (Cutter et al., 2008). In addition, all these variables of the economic component operate yearly on a local (community) scale, except for national income and parts of the tax base, which are governed at national scale. Diversity in the national and regional economy provides greater resilience because employment is distributed across multiple economic sectors and reduces the possibility of high unemployment due to the failure of a single dominant sector (Sherrieb et al., 2010). Moreover, communities that are highly dependent on employment from extractive processes (e.g. oil and gas extraction, mining, and quarrying) and tourism are more likely to be affected by a natural hazard (Burger, 2017; Mayer et al., 2014). Considering employment within different economic sectors, resilience is lowest in Meiringen because the community is highly dependent on a single sector consisting of tourism and retail trade (Fig. S3b).

In MC-CHLS, population is driven by birth rate, death rate and migration rate in the community (Fig. 4, shaded purple). The population in MC-CHLS contains information on community age structure because resilience is lower in communities with higher fraction of elderly residents that have a lower capacity to respond to hazards (Morrow, 2008). With respect to the communities in the Oberhasli, a greater proportion of aging population (>64 years) in Guttannen potentially makes it less resilient to hazards (Fig. S3c). In case of migration, immigration to and emigration from the community influences the total population. If employment opportunities and household level income decrease due to the repeated impacts of natural hazards (Joakim et al., 2016; Prior et al., 2017), emigration will likely increase, as people are likely to move away from the community, leading to a decrease in population. In contrast, immigration increases the total population in the community. Evidence shows that different groups of people are attracted to mountain communities. One of these groups are new highlander entrepreneurs who move to peripheral Alpine communities (Mayer and Meili, 2016). Other mountain destinations create competitive advantage by building fibre-optic networks allowing for high-speed data access. They attract temporary visitors in form of firms, students and workers that are searching for a "third place" to work and recover at the same time. A recent example is the MiaEngiadina project, offering also a center with Co-Working spaces and rooms for meetings and conferences (Albani, 2017). A further strategy of mountain communities is to enhance employment in specific sectors, such as in the tourism and construction industry by investments in infrastructure like cable car facilities or accessibility by train to counter decreasing overnight stays (Haisch et al., 2017). The impact by shock such as natural hazards, i.e. a significant damage to the built environment also negatively affects employment. For example, in extreme circumstances when natural hazards are reoccurring and/or of high magnitude, businesses are destroyed, and people will leave the community (Zhang et al., 2009). Employment is positively linked to household, regional and national income. Thus, a decrease in employment (i.e. percentage of the population in employment) also increases pressure on the tax base as more people tend to rely on social benefits (Burger, 2017; Keating et al., 2014; Mayer et al., 2014).

In MC-CHLS, the social system (Fig. 4, shaded yellow) depicts the relationship among the components of social institutions, which consists of five variables, namely: 1) awareness and perception; 2) political pressure; 3) social capital; 4) health; and 5) social dependency (definitions of variables provided in Table 1S). The severe impact of floods leads to deterioration in health status in terms of injuries, disabilities and death caused in the community. Ultimately, this increases social dependency (e.g. disability, social benefits recipients) in the community, as more people tend to rely on social benefits (Hanger et al., 2018; Svetlana et al., 2015; Keating et al., 2014). The impacts and the resulting dependency, in turn increases political pressure to make or change decisions, as well as the rules and regulations that reduce risk and increase

resilience to natural hazards in the community. The awareness and perception (e.g. percentage of the population receiving warnings and training) of people involved in natural hazard risk preparedness can enhance skills and knowledge, reduce damage to settlements from natural hazards and influence political pressure to make decisions about reducing risk and increasing resilience to natural hazards at the community level.

3.3. Feedbacks

We identified the feedback (positive and negative) loops within and between the biophysical and socioeconomic components of Swiss Alpine communities similar to those found in Oberhasli. In summary, a positive (reinforcing) feedback loop subsequently intensifies an increasing or decreasing growth in a system, whereas, a negative feedback is often known as a balancing loop as it acts to reduce or counteract the results of a change or growth in the system. Furthermore, we describe how these interdependencies ultimately have an effect on risk and community resilience. In total MC-CHLS contains (Table 1) five feedback loops: 1) natural hazard mitigation loop (Fig. S4); 2) land use, land cover change and employment loop (Fig. S5); 3) land use, land cover change and damage loop (Fig. S6); 4) economy and demographics loop (Fig. S7) and 5) health and population loop (Fig. S8).

The natural hazard mitigation loop (Fig. S4) has a balancing loop, as increased debris flow increases damage to settlement, which eventually increases political pressure due to the increase in awareness and perception of community to implement protective infrastructure that reduces debris flow. For flood hazards (Fig. S4), the loop can be either balancing or reinforcing depending on the magnitude of the flood and the existence of flood protection. A balancing feedback loop occurs if damage to settlements increases, protective infrastructure is constructed, and flood risk is reduced for small magnitude floods. In contrast, high magnitude floods can result in a balancing feedback loop if protective infrastructure (e.g. levees) laterally restricts channel form, leading to increases in flow velocity and depth, which in turn increases flood risk. However, because MC-CHLS considers the potential geomorphic effect of levees, flood risk during high magnitude events remains unclear because over time channel incision may occur and reduce flood risk (Zischg et al., 2018).

Both Fig. S5 and Fig. S6 depict examples of a reinforcing and a balancing loop respectively in MC-CHLS. In Fig. S5, when community employment increases, both regional income and tax base increases, which ultimately reduces political pressure and restrictions on land. Under these circumstances, a demand from the inhabitants encourages land use change towards community expansion or densification. Ultimately, this may increase the possibility of damage to the community in the absence of protective infrastructure, and cause the loss of economic value (Getzner et al., 2017). Therefore, there is a balancing loop (Fig. S6), in which, changes in land use may increase damage to settlement, which eventually decreases both household income and tax base, which in turn increases political pressure to perform land use changes that may include settlement abandonment and relocation (Menoni and Pesaro, 2008). These possible pathways focus on the prevention of further development that result in increased community resilience and long-term reductions in flood risk because people and assets will no longer be exposed to flooding.

The population sub-model (Fig. S7 and Fig. S8) is influenced by health, economic and demographics variables. In Fig. S8, there is a reinforcing loop; where increased population leads to increased employment, which increases both regional income and tax base, which ultimately, improves the health that leads to higher population. In addition, Fig. S7 illustrates that increased population and employment increases household income, which reduces the out-migration to urban areas, which in turn maintains or increases population. However, for both loops, population does not always have an increasing effect on employment, because a community has limits on employment

opportunities and additional growth in population will likely cause unemployment.

The combination of the natural hazard mitigation (Fig. S4) and land use, land cover and damage (Fig. S6) feedback loops contain the components that result in the “levee effect” (White, 1945). To explain the levee effect with MC-CHLS, a hypothetical mountain community in its inception may have existed geographically distant from a river and these conditions produced low flood risk and low community resilience because less economic gain was possible with limited access to the river. Additionally, the river was in a relatively natural state because the community did not need protective infrastructure (e.g. levees). Over time, community settlement occurred closer to the river and this increased flood risk because more assets were exposed to flooding, but community resilience increased because of economic gain. In this example, the natural hazard mitigation feedback loop (Fig. S4) in MC-CHLS is triggered after a flood event that produces sufficiently high damages that raise community perception and awareness towards flooding. Consequently, the community increases political pressure to mitigate flood risk through the construction of levees. Levees provide a sense of security by eliminating damages to the community for smaller flood events and this attracts economic opportunities, which increase household income and community tax base (land use, land cover and damage loop, Fig. S6). With economic growth comes lower political pressure and restrictions on land use changes, which can result in development on flood prone areas. Returning to the natural hazard mitigation feedback loop, although levees can protect the community from smaller floods, they concentrate flow and increase the risk of extreme flood events for communities.

4. Discussion

In this section, we take a step further and begin to contemplate the inputs, outputs, policy implications and challenges to operationalizing MC-CHLS. In particular, the development of MC-CHLS into a computer model that provides information for natural hazard and socioeconomic policy at the national and sub-national level. For example, in the case of Switzerland, there is a lively debate among policymakers and politicians about the future development potential of Alpine Regions (e.g. various efforts in the parliament about the future of Swiss mountain regions such as Motion Maissen or Postulat Brand). This debate, however, is often biased towards one perspective such as for example economic or natural hazards and practitioners rarely consider the interrelated nature of natural hazards and socioeconomic dynamics.

4.1. Implications of MC-CHLS for policy in the Swiss Alpine communities

MC-CHLS contains (Table 1) three balancing loops and two reinforcing loops. The interactions among the variables (Sections 3.1 and 3.2) and feedbacks (Section 3.3) within and between human and natural systems underpin the dynamics (e.g. stability, instability) in the system (Biggs et al., 2012). For example in the case of flooding, the natural hazard mitigation loop (Fig. S4) has both reinforcing and balancing loop, which may be the cause of system instability by increasing the risk of flooding due to channel formation and changes in water depth in response to adaptation through protective measures (Zischg et al., 2018). Though it is not a major feedback loop, the long-term increase in temperature and precipitation is believed to increase flood risk. In particular, the possibility of increase in temperature (+2 °C to +7 °C) and precipitation (10%–20%) will increase the frequency and intensity of flood risk by the end of the century (NCCS, 2018; Köplin et al., 2014). Therefore, the flood protective infrastructure (e.g. levees) needs to consider the future climate scenarios (NCCS 2018) and the reinforcing feedbacks among infrastructure, flow velocity and depth; otherwise, it may jeopardize the efforts of reducing risk and increasing the risk in the Swiss Alpine region. Though the increase in vegetation (Bathurst et al., 2017; Gago-Silva et al., 2017) may decrease flood risk

(Rahman et al., 2015), increase in population (e.g. 28% increase by 2060) (FSO, 2010) may encourage land use change towards community expansion or densification, which in turn, may increase the possibility of damage and decrease the resilience of communities in the long term (Getzner et al., 2017). In such a case, if short-term socio-economic shocks (e.g. financial crisis) combine with these scenarios, it may raise the prospect of 'perfect storm' scenarios (Dearing et al. 2012) with a greater likelihood of negative impacts and further socio-economic challenges on Swiss Alpine communities. The balancing loops such as natural hazard mitigation, economy and demography loops, land cover change and damage loop may reduce the risk and increase resilience through reducing the aggregated impacts of reinforcing loops. However, all these may rely on political pressure and community awareness, which could be highly challenging considering the future climate, population and land use scenarios in Switzerland. In addition, besides the dynamic relationships such as interactions and feedbacks, identification and understanding of other dynamic relationships such as nonlinearities and delays (Dearing et al., 2015; Biggs et al., 2012) are required to ensure the sustainability of Swiss Alpine communities. For example, it is important to investigate how long the vegetation cover can reduce the run-off and at what point, it reduces the resilience, which can cause sudden and massive floods in response to climate change. Furthermore, the delay between melt generation and emergence as runoff (Sing et al., 2011) and community awareness and political pressure, could also be substantial to consider in managing the risk and resilience of Swiss Alpine community. Therefore, dynamic and integrated modelling approaches that can guide the selection of adaptation for reducing risk and increase resilience for the coming decades will be essential to address these concerns considering the following scenarios at Section 4.2.

4.2. Scenarios and MC-CHLS outputs

MC-CHLS can be driven with the combination of climate and socio-economic scenarios that explore the potential futures of mountain communities. Scenarios can consider both biophysical and socioeconomic shocks as inputs. Biophysical shocks are driven by precipitation and temperature and are shock entry points in MC-CHLS. Biophysical shocks are highly correlated with climate extremes that include intense rainfall and hot temperature extremes, but MC-CHLS considers that a direct link between weather and natural hazard does not always occur. MC-CHLS recognizes that conditions antecedent to the weather event largely determine if a natural hazard occurs, and these conditions include the availability of sediment for transport, land cover, and channel conveyance capacity. Specifically for Switzerland, climate change scenarios have been developed that consider 1.4–4.8 °C increase in mean temperature by the end of the century (Appenzeller et al., 2011). These scenarios suggest that during this century hot temperature extremes are expected to increase in frequency, intensity and duration, while intense rainfall will potentially increase in summer and winter. Considering these changes in weather extremes, multi-decadal time series of precipitation and temperature can be generated for input into MC-CHLS that

result in low, moderate and high probabilities of extreme event occurrence.

In MC-CHLS socioeconomic scenarios for variables that operate on longer time scales can adopt as a template the IPCC Special Report on Emission Scenarios (SRES) (Alley, 2007) (Table 2) or more recently developed Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2014). These global scale scenarios explore combinations of economic and environmental futures that consider level of environmental concern, agricultural subsidies, globalization of world markets, and self-sufficiency of regional economies. Ideally for MC-CHLS, global socioeconomic scenarios will require further refinement to adequately consider developments of socioeconomic variables at community scales. In MC-CHLS, short-term socioeconomic shocks can be superimposed in time upon these long-term scenarios. For example, short-term socio-economic shocks can be induced through economic (financial) crises that can lead to job losses in industries (e.g. construction, tourism or energy) upon which most Swiss Alpine communities depend on. Job losses can lead to out-migration, a closure of infrastructure facilities like schools and a decrease in the community tax base (Fig. 4). As such, these shocks increase both risk and decrease resilience to natural hazards or further socio-economic challenges.

4.3. Challenges in operationalizing MC-CHLS

There are major challenges to operationalizing MC-CHLS that pertain to data, model development and constraining uncertainty. More than likely, a reduction in model complexity is required to operationalize the human component of MC-CHLS due to data limitations for variables and the difficulty in measuring abstract variables. For example, variables like community's awareness and perception to natural hazards and political pressure may not be readily available and require data collection through surveys. The lack of data for abstract variables is further compounded because time series are needed to determine how variables change before, during and after biophysical and socioeconomic shocks.

A coupled component modelling approach can be adopted in operationalizing MC-CHLS for Swiss Alpine catchments and communities, where existing models from different disciplines are linked to simulate biophysical and human processes (Kelly et al., 2013; Zischg, 2018). For example, a model platform for the biophysical component of MC-CHLS could be a landscape evolution model (LEM) that simulates hill-slope, rainfall-runoff, hydrodynamics, land surface erosion and channel processes (Tucker and Hancock, 2010) at the catchment scale. However, LEM cannot model the human components of MC-CHLS. The human component of MC-CHLS can be developed using system dynamics modelling. System dynamics modelling can be useful to capture the complex dynamics (interaction, feedback) between human and natural systems. The modelling components such as stocks, flows (out flow and inflow) and converters are enabled to capture the dynamics (interaction and feedback) between human and natural systems. System dynamics modelling can be useful in overcoming the challenges of data unavailability when modelling a system (Hossain et al., 2017b; Ford

Table 2
Socioeconomic scenarios for Swiss mountain communities (adopted from Price et al., 2015).

	Emphasis on economics	Emphasis on environment
Globalization (homogenous world)	A1	B1
	Low population growth	Low population growth
	Low national and regional income	Low national and regional income
	Low subsidies	High subsidies
Regionalization (heterogeneous world)	A2	B2
	High population growth	Moderate population growth
	High national and regional income	Moderate national and regional income
	Low subsidies	High subsidies
	Low land use restrictions	High land use restrictions

2010). In particular, in MC-CHLS, the parameterization of the variables such as awareness and damage to settlement, social capital and political pressure could be highly challenging, due to difficulty in quantifying the relationships. In such a case, the use of a scale (e.g. high to low) based approach using graphical function in system dynamics modelling may help resolve this challenge of operationalizing variables (Hossain et al., 2017b).

Linking the biophysical and human components of MC-CHLS will be one of the major challenges in operationalizing MC-CHLS. This may involve the development of the human component in a system dynamics modelling platform and translating the code of the human component to the programming language of the LEM (Naimi and Voinov, 2012). Afterwards the translated code of the human component can be embedded in the code of the LEM to produce a tight coupling between the biophysical and human components of MC-CHLS.

Furthermore, incorporating the spatial heterogeneity and the selection of aggregated behavior over individual level behavior could also pose challenges in operationalizing MC-CHLS. Although, system dynamics modelling is suited for modelling the aggregated behavior of a system, a limitation of this approach is the difficulty in spatially representing the dynamics of human and natural systems across different scales (Hossain and Speranza, 2020). As an alternative, the human component of MC-CHLS could be developed using agent based modelling (ABM) that can capture spatial dynamics, and is useful for modelling individual (e.g. households, agents) behavior in response to flood risk (Borshchev and Filippov, 2004). In particular, it can be useful in understanding the human components of MC-CHLS such as political pressure, awareness and behavior of community towards social benefits. However, in ABMs it is highly challenging to replicate behavior of human and natural systems, particularly when systems are less well known and unexpected (e.g. shocks) behaviors and patterns (Filatova et al., 2013; Verburg et al., 2016) are the key features of the system.

4.4. Limitations and further improvement

This study develops the first conceptual model of Mountain Community Coupled Human Landscape System by considering the dynamic relationships (e.g. interactions, feedbacks) within and between human and natural systems. In general, the approach of this study can also be used for analyzing and modelling human and natural systems in other data-poor areas of mountain communities. In addition, this conceptual model can later be used as a “blueprint” for a computer model that can: 1) provide information on future trajectories of mountain community risk and resilience, 2) investigate how mountain communities buffer socio-economic (e.g. economic downturn) and biophysical (e.g. floods) “shocks”, 3) determine which shocks have a greater effect on mountain communities, and (4) serve as a basis for transdisciplinary deliberative resilience building processes.

However, our study was limited to identifying and understanding the variables, processes and dynamic relationships among them using a system dynamics approach. In particular, considering the data (long-term) limitation, we adopted the approach of literature review and engagement of interdisciplinary team with experience in Alpine regions in order to develop the conceptual model, which was supported by the discussion with stakeholders in the community and feedback from the regional, national and international scientific community. This can be improved in the future by: 1) operationalizing and comparing the conceptual model in other natural hazard prone regions; 2) using a participatory approach (e.g. Hossain et al., 2019) to develop a conceptual model which can be compared with our existing MC-CHL model before developing a final conceptual model required as an input in dynamic modelling approaches; 3) integrating more human agency in the model by linking it with an agent-based modelling approach and collecting conceptual data; 4) adopting a statistical approach (e.g. Barbosa et al., 2016; Santos-Martin et al., 2013) to understand the

causality within and between human and natural systems in order to develop a conceptual model, where long-term dataset is available.

5. Conclusions

This study makes a first attempt to develop a conceptual model by considering complex dynamics (interactions and feedbacks) between human and biophysical systems in Swiss Alpine communities. Key variables and processes were defined and feedbacks within and between human and natural components were identified. Dominant feedback loops were visualized and traversed to illustrate potential changes in risk and community resilience resulting from socioeconomic changes and natural hazards.

The conceptual model provides an overview of the processes that should be considered when developing policy to reduce risk and increase community resilience in Swiss Alpine communities. Besides developing a conceptual model with real-world examples, the conceptual model provides guidance in developing a numerical model that can quantitatively predict risk and community resilience. Operationalization of the conceptual model will require complexity reduction due to data limitations and should adopt a scenario approach that explores uncertainty in driving variables and model processes.

Declaration of competing interest

The authors have no other conflicts of interest to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.138322>.

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